Magnetically Damped Furnace
Bitter Magnet Coil 1

FINAL REPORT

M. D. Bird
INTRODUCTION

A magnet has been built by the National High Magnetic Field Laboratory for NASA on a cost reimbursement contract. The magnet is intended to demonstrate the technology and feasibility of building a magnet for space based crystal growth. A Bitter magnet (named after Francis Bitter, its inventor) was built consisting of four split coils electrically in series and hydraulically in parallel. The coils are housed in a steel vessel to reduce the fringe field and provide some on-axis field enhancement. The steel was nickel plated and Teflon coated to minimize interaction with the water cooling system. The magnet provides 0.14 T in a 184 mm bore with 3 kW of power.

TEST PROCEDURE AND DATA

I MASS

| Maximum mass of magnet empty: | 100 kg |
| Measured mass of magnet empty: | 77 kg |
| Measured mass of magnet full: | 79 kg |
| Measured by: | O'Reilly, Loffelbein |
| Equipment Used: | Pelouze Model 4040 400 lb Capacity Digital Scale +/- 0.2 kg |

II STRUCTURAL AND MECHANICAL

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>(g's)</th>
<th>(m/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.6</td>
<td>133.416</td>
</tr>
</tbody>
</table>

SPRING FORCES

| Desired Clamping force (N) | 2000 |
| Spring stiffness (N/mm)   | 21.3 |
| Spring free length (mm)   | 7.94 |
| Spring solid height (mm)  | 4.9  |
| Max. spring displacement (mm) | 3.04 |
| Max. spring force/spring (N) | 64.8 |
| # of springs              | 50   |
| Max. spring force/coil (N) | 3238 |
| Max. spring force tot (N)  | 12950 |

COIL MASSES AND G FORCES

<table>
<thead>
<tr>
<th>Coil #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>coil mass (kg)</td>
<td>7.4</td>
<td>9</td>
<td>11.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Accel. Force (N)</td>
<td>987</td>
<td>1201</td>
<td>1494</td>
<td>2028</td>
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<tr>
<td>Total mass (kg)</td>
<td>42.8</td>
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<td></td>
<td></td>
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<tr>
<td>Total force (N)</td>
<td>5710</td>
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### HYDRAULIC FORCES

<table>
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<th>Water Pressure (MPa)</th>
<th>0.02</th>
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<tr>
<td>Head area (mm^2)</td>
<td>65182</td>
</tr>
<tr>
<td>Pressure load (N)</td>
<td>1304</td>
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### DESIGN FORCE

| Design force (N) | 14254|

### STAND-OFF ROD COMPRESSION

<table>
<thead>
<tr>
<th>length (mm)</th>
<th>53</th>
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<tr>
<td>diameter of rods (mm)</td>
<td>5</td>
</tr>
<tr>
<td>number of rods</td>
<td>24</td>
</tr>
<tr>
<td>area (mm^2)</td>
<td>471</td>
</tr>
<tr>
<td>Stress (MPa)</td>
<td>30</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>210</td>
</tr>
<tr>
<td>Safety factor</td>
<td>6.9</td>
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### HEAD DEFLECTION: see Roark's formulas for stress and strain pg. 405

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<tr>
<th>Outer radius</th>
<th>a (mm)</th>
<th>172</th>
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<tr>
<td>Inner radius</td>
<td>b (mm)</td>
<td>94</td>
</tr>
<tr>
<td>Thickness</td>
<td>t (mm)</td>
<td>7</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>E (MPa)</td>
<td>2.10E+05</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>nu</td>
<td>0.30</td>
</tr>
<tr>
<td>Bending stiffness</td>
<td>D</td>
<td>6.60E+06</td>
</tr>
<tr>
<td>distributed load</td>
<td>q (MPa)</td>
<td>2.19E-01</td>
</tr>
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</table>

| C1            | 0.4392 |
| C7            | 0.5839 |
| C4            | 0.9957 |
| L11           | 0.0014 |
| L14           | 0.0118 |
| L17           | 0.0768 |

Displacement at inner radius

- simple support
  - yb (mm) | 1.64 |
  - thetb(rad) | 0.02 |
  - theta(rad) | 0.02 |

- clamped
  - yb (mm) | 0.11 |

Moment at outer radius | Mra (N) | -452 |
Stress at outer radius | Sra (MPa) | -55.4 |
Yield Stress | Sy (MPa) | -210 |
safety fator | 3.79 |
**VESSEL SHELL TENSION**
- vessel section (mm\(^2\)) 5404
- vessel Sss (MPa) 2.64
- vessel strain 1.26E-05
- vessel length (mm) 218
- vessel DL (mm) 0.27
- yield stress (MPa) 210
- safety factor 80

**SCREW TENSION**
- screw section (mm\(^2\)) 14.2
- # of screws 18
- total moment at outer radius (Nmm) -488761
- moment per screw (Nmm) -27153
- moment arm (mm) 6.25
- screw tension (N) 4345
- proof load (N) 8230
- safety factor 1.89

**III MATERIAL COMPATIBILITY**
A complete drawing package was sent to NASA and was approved before construction began. A package of as-built drawings is enclosed. Materials in contact with coolant consist of the following: stainless steel, nickel, Teflon, Kapton.

**IV. DIMENSIONS**

<table>
<thead>
<tr>
<th></th>
<th>Required</th>
<th>Measured</th>
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<tbody>
<tr>
<td>Length</td>
<td>238.1 mm max.</td>
<td>239.44, 239.58 mm</td>
</tr>
<tr>
<td>Inside diameter</td>
<td>184.2 mm min.</td>
<td>184.24, 184.26 mm</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>361.95 mm max.</td>
<td>341.78, 341.42 mm</td>
</tr>
<tr>
<td>Measured by:</td>
<td>Bird, O'Reilly</td>
<td></td>
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<tr>
<td>Equipment used:</td>
<td>Mitutoyo 0-55 cm caliper</td>
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</table>

**V. FIELD STRENGTH AND HOMOGENEITY**
The water flow through the magnet was set at 640 ml/10 sec (230 kg/hr) as measured with a graduated cylinder and stopwatch. The current was set at 20.88, 27.87 and 31.86 Amps as measured by a shunt and multimeter. The voltage across the coil was measured at 52.28, 76.80 and 92.99 Volts for the three current settings, respectively. The electrical power consumed during the three measurements was 1092, 2140, and 2963 Watts, respectively. The field was mapped along the axis of the magnet using a Hall probe, Hall probe holder, and gaussmeter. The recorded data follows:
<table>
<thead>
<tr>
<th>pos. (mm)</th>
<th>1 kW Field (mT)</th>
<th>2 kW Field (mT)</th>
<th>3 kW Field (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>76.5</td>
<td>105.9</td>
<td>124.4</td>
</tr>
<tr>
<td>64</td>
<td>81.3</td>
<td>112.6</td>
<td>131.8</td>
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<td>79</td>
<td>83.9</td>
<td>116.2</td>
<td>135.3</td>
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<tr>
<td>94</td>
<td>84.8</td>
<td>117.6</td>
<td>136.5</td>
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<tr>
<td>109</td>
<td>85.1</td>
<td>118.0</td>
<td>136.4</td>
</tr>
<tr>
<td>124</td>
<td>85.5</td>
<td>118.4</td>
<td>136.4</td>
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<td>139</td>
<td>86.1</td>
<td>119.0</td>
<td>136.8</td>
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<td>86.6</td>
<td>119.5</td>
<td>136.9</td>
</tr>
<tr>
<td>169</td>
<td>86.1</td>
<td>118.7</td>
<td>135.4</td>
</tr>
<tr>
<td>184</td>
<td>83.7</td>
<td>115.2</td>
<td>130.9</td>
</tr>
<tr>
<td>199</td>
<td>78.4</td>
<td>107.9</td>
<td>122.4</td>
</tr>
</tbody>
</table>
Field variation over 150 mm: 1 kW = 8.2%, 2 kW = 11.4%, 3 kW = 9.1%. Specification: < 10% at 3 kW.
Equipment used: ABB/Alpha Scientific 20kA, 500 V power supply; Weston KS9442-L6 150 A, 50 mV shunt; Keithley 2001 Multimeter (2), Lakeshore 420 Gaussmeter; Lakeshore MMA-2502-VG axial metal stem Hall probe; NHMFL RES/TOL-1 hall probe holder, Kartell, 1000 mL graduated cylinder; Fischer-Scientific Digital Dual Channel Thermometer; Micronta 63-5012 LCD electronic stopwatch

VI. POWER
See item V.

VII. ELECTRICAL ISOLATION

Required line to chassis isolation: 2 Megohms
Measured line to chassis isolation: 500 Megohms at 500 V
Equipment used: AEMC model 1000 Megohmmeter

VII. PHYSICAL POWER INTERFACE

The MDF-BC1 provides screw lug connectors capable of utilizing 8 gage wire within the zone shown in Figure 3.1.3-1 of the MDF-BC1 specifications.

VIII. COOLANT LOOP PHYSICAL CONNECTIONS

Fluid connectors are male 37 degree flare fittings size 6 per commercial equivalent of military standard 3365.

IX. INLET/OUTLET TEMPERATURE OF MDF-BC1 COOLANT

Set flow at 232 kg/hr. and measure temperature rise at 1, 2 and 3 kW.

<table>
<thead>
<tr>
<th>I (Amps)</th>
<th>V (Volts)</th>
<th>Tin (C)</th>
<th>Tout (C)</th>
<th>Q (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.88</td>
<td>52.28</td>
<td>12.4</td>
<td>13.3</td>
<td>230</td>
</tr>
<tr>
<td>27.87</td>
<td>76.80</td>
<td>12.5</td>
<td>15.5</td>
<td>230</td>
</tr>
<tr>
<td>31.86</td>
<td>92.99</td>
<td>12.6</td>
<td>19.4</td>
<td>230</td>
</tr>
</tbody>
</table>

Performed by: Bird, Bole, Loffelbein, O'Reilly
Equipment used: see V
X. COOLANT FLOW RATE/ PRESSURE DROP

<table>
<thead>
<tr>
<th>Flow (mL/10s)</th>
<th>Flow (kg/hr)</th>
<th>DP (psi)</th>
<th>DP (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>184</td>
<td>1.2</td>
<td>8</td>
</tr>
<tr>
<td>610</td>
<td>220</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>630</td>
<td>227</td>
<td>2.0</td>
<td>14</td>
</tr>
<tr>
<td>700</td>
<td>252</td>
<td>2.0</td>
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<tr>
<td>740</td>
<td>266</td>
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<td>830</td>
<td>299</td>
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<td>17</td>
</tr>
<tr>
<td>870</td>
<td>313</td>
<td>3.0</td>
<td>21</td>
</tr>
<tr>
<td>900</td>
<td>324</td>
<td>3.0</td>
<td>21</td>
</tr>
</tbody>
</table>

Specification: <34.5 kPa at 232 kg/hr.
Measured by: Bird, O'Reilly
Equipment used: Wika -30 in. Hg/ +30 psi gage; 1000 mL graduated cylinder; Pulsar quartz watch.

XI. COOLANT COMPATIBILITY

A complete drawing package was sent to NASA and was approved before construction began. Materials in contact with coolant consist of the following: stainless steel, nickel, Teflon, Kapton.

Magnet water specification at the NHMFL:

- Total dissolved solids (as CaCO₃) 50 ppb
- Total silica (as SiO₂) 10 ppb
- Sodium (as CaCO₃) 40 ppb
- Resistivity 6 Megohm-cm
- Dissolved Oxygen 0.02 - 0.03 ppm

XII. ATMOSPHERE

The MDF-BC1 will operate in the following atmospheres:

- 0.1 bar Argon
- 18-45 degrees Centigrade air with 40 - 90 % relative humidity.

XIII. EXTERNAL FIELD

The field external to the magnet has been measured at the midplane 200 mm from the outside surface of the MDF-BC1 shielding:

- Required field: 3 kw
- Measured field: 2.3 gauss
- Performed by: Bird, Bole, Loffelbein
IXV. PACKAGING

The MDF-BC1 is adequately packaged for damage-free handling. After operation it was drained and dried by blowing compressed air through it for approximately 3 hours. It was then filled with Helium gas and closed.

CONCLUSIONS

The magnet project was successfully completed. Additional magnets could be built if requested. The primary change that could be made to attain higher field and/or uniformity would be to make the magnet longer. However, for this first magnet, the overall length was constrained in the contract to be less than or equal to 238.1 mm. The NHMFL looks forward to receiving results of the tests to be performed at NASA.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE Y
3. N PLATE (0.013) THICK PER MIL-C-28074E
4. TFEFLON COAT (0.050±0.0127) THICK
5. ALL DIMENSIONS ARE AFTER PLATING AND COATING.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. M. PLATE 0.013 THICK PER MIL-C-26074E
4. TFELOM COAT (0.051+0.0127) THICK
5. ALL DIMENSIONS ARE AFTER PLATING AND COATING.

---

GENERAL TOLERANCES
1. PL DEC 8.25
2. PL DEC 8.10

MATERIAL
6061-7651 ALUMINUM ALLOY

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES

SIZE
RES/HOU-12-02

SCALE 1/1
SHEET 1 OF 1
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE 2/Y
3. NI PLATE 0.013 THICK PER MIL-C-26074E
4. TFE FOAM 0.054X0.0127 THICK
5. ALL DIMENSIONS ARE AFTER PLATING AND COATING.
6. REF: O-RING SIZE .103 W X 12.24 ID.
7. USE: O-RING SIZE .070 W X 7.34 ID.

REVISIONS

<table>
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<th>ZONE</th>
<th>REV.</th>
<th>DESCRIPTION</th>
<th>DATE</th>
<th>APPROVED</th>
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<td>19/12/95</td>
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<tr>
<td>B</td>
<td></td>
<td>CHANGE NI AND TFE FOAM SPECS</td>
<td>27/12/95</td>
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<tr>
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<td>26/06/96</td>
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GENERAL TOLERANCES
1 PL. DEC .25
2 PL. DEC .10
ANGLES 8°

MATERIAL:
1026 CRS

DIMENSIONS ARE IN MILLIERS

COVER, UPPER

RES/HOU-12-03A

SCALE 1/1

SHEET 1 OF 1
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. ELECTROLESS Ni PLATE 0.013 THICK PER MIL-C-26074E
   (10 - 12% PHOSPHORUS CONTENT), ALL OVER, INCLUDING TAPPED HOLE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES.
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE V.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
FLAT PATTERN

NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: Cu, 0.2 THICK
4. ELECTROLESS Ni PLATE 0.013 MAX THICKNESS EACH SIDE
PER MIL-C-26074E(10-12% PHOSPHORUS CONTENT)
5. TEFLOM COAT (0.05+0.0127) THICK, MASK AS INDICATED

D
C
B
A

REVISES
ZONE
REV
DESCRIPTION
DATE
APPROVED
- INITIAL RELEASE
A CHNG D MATERIAL TO COPPER 18/12/95
B CHNG D COIL D IN NAME 19/12/95
C CHNG D DESIGN 07/03/97

NATIONAL HIGH MAGNETIC FIELD LABORATORY
1900 EAST PULLI DR. DR. TALLAHASSEE, FLORIDA 32306-4005

BUS BAR, COIL D

SEE NOTE 3.
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLON, 1.0 THICK STOCK

GENERAL TOLERANCES

NATIONAL HIGH MAGNETIC FIELD LABORATORY
1900 EAST PAUL DOMINIC DRIVE
TALLAHASSEE, FLORIDA 32306-9005

THIRD ANGLE PROJECTION

MATERIAL: SEE NOTE 3.

NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLON, 1.0 THICK STOCK

REVISIONS

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<td>C</td>
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<td>CHNGD HOLE PATTERN AND DIMS</td>
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NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFFLON, 1.0 THICK STOCK

REVISIONS

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<td>CHANGED HOLE PATTERN AND DIMS</td>
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NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOM, 1.0 THICK STOCK

REVISIONS

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<td>D</td>
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<td>MFG RELEASE</td>
<td>29/09/96</td>
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</tr>
</tbody>
</table>

GENERAL TOLERANCES

1. PL DEC R=2.75
2. PL DEC R=8.10
ANGLES ±1°

MATERIAL: TEFLOM, 1.0 THICK STOCK

SEE NOTE 3.

DO NOT SCALE DRAWING

SCALE 1/1

SHEET 1 OF 1
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE

2X R3.2

R12.0

#5.5

5.0

2.0
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: Cu 0.2 THICK
4. ELECTROLESS Ni PLATE 0.013 MAX THICKNESS EACH SIDE
PER MIL-C-28074E (10-12% PHOSPHORUS CONTENT)
5. TEFLOW COAT (0.05±0.0127) THICK, MOLD AS INDICATED

OWN TEFLOW COATING THIS FACE

OWN TEFLOW COATING THIS FACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLON

HOLE/NOTCH DETAIL - SCALE 5:1

SECTION A-A - SCALE 5:1

16X #2.50
2 PL (O AND OD)
SPACED AS SHOWN

50X #2.50
6 X 10 X 1/16 X 3

GENERAL TOLERANCES

1 PL DEC 2.25
2 PL DEC 6.10
ANGLES 3.1

NATIONAL MAGNETIC FIELD LABORATORY
1800 EAST PAUL DRAC DRIVE
TALLAHASSEE, FLORIDA 32308-4005

INSULATOR, SPACER, COIL B

MATERIAL: SEE NOTE 3

UNLESS OTHERWISE SPECIFIED: SCALE 5:1
NO SCALE DRAWING

RES/HOU-12-17

REV B

DO NOT SCALE DRAWING
APPLICATION

NEXT ASSY

FINISHED AS SHOWN

DIMENSIONS ARE IN MILLIMETERS

2 PL DEC 2.25
2 PL DEC 6.10
ANGLES 3.1

16X #2.50
2 PL (O AND OD)
SPACED AS SHOWN

50X #2.50
6 X 10 X 1/16 X 3

GENERAL TOLERANCES

1 PL DEC 2.25
2 PL DEC 6.10
ANGLES 3.1

NATIONAL MAGNETIC FIELD LABORATORY
1800 EAST PAUL DRAC DRIVE
TALLAHASSEE, FLORIDA 32308-4005

INSULATOR, SPACER, COIL B

MATERIAL: SEE NOTE 3

UNLESS OTHERWISE SPECIFIED: SCALE 5:1
NO SCALE DRAWING

RES/HOU-12-17

REV B

DO NOT SCALE DRAWING
APPLICATION

NEXT ASSY

FINISHED AS SHOWN

DIMENSIONS ARE IN MILLIMETERS
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: TEFLOM

GENERAL TOLERANCES
INSULATOR, SPACER, COIL D

SECTION A-A - SCALE 5:1

HOLE/NOTCH DETAIL - SCALE 5:1

5x5 @ 3.2

16x Ø2.50
EQUALLY SPACED
Ø0.10 @ 1.5 G

270.00
3.8
267.00
269.50

16x ©0.51 Ø0.10.0.100.15

DIMENSION

3.00 STOCK

9/03/06

8/15/95

12/15/95

12/15/95

12/15/95

MFG. RELEASE

DATE

REV

DESCRIPTION

INITIAL RELEASE

DRAWN BY

REVISIONS

DRAFTSMAN

DRAFT

ENTRY

INCHES/MILS.

CM/000"
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE

20.0

173.40

213.4

6.35 STOCK

31.75 STOCK

31.75

6.35

4X 5.0

6X #6.4 THRU

20.0

86.7

173.4

20.0

19.05
NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINED SURFACE
3. MATERIAL: C10100, C10200 OR C11000, HALF HARD
4. ELECTROLESS Ni PLATE 0.013 MAX THICKNESS EACH SIDE
   PER MIL-C-26074E(10-12% PHOSPHORUS CONTENT)
1. REMOVE ALL BURRS AND SHARP EDGES
2. UNLESS OTHERWISE SPECIFIED MACHINE SURFACE
3. MATERIAL: C10100, C10200, OR C11000, 0.2 THICK, HALF HARD
4. ELECTROLESS N. PLATE 0.013 THICK PER MIL-C-26074E
   (10 - 12% PHOSPHORUS CONTENT)
5. * - BOLT CIRCLE DIAMETER
6. # - COOLING HOLE ANGLE

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ALL B.C. DIAMETERS ARE BASIC
SEE NOTE 5